



New NASA SEE LEO Spacecraft Charging Design Guidelines—How to Survive in LEO Rather Than GEO

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NEW NASA SEE LEO SPACECRAFT CHARGING DESIGN GUIDELINES – HOW TO SURVIVE IN LEO RATHER THAN GEO

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Abstract

It has been almost two solar cycles since the GEO Guidelines of Purvis *et al* (1984) were published. In that time, interest in high voltage LEO systems has increased. The correct and conventional wisdom has been that LEO conditions are sufficiently different from GEO that the GEO Guidelines (and other GEO and POLAR documents produced since then) should not be used for LEO spacecraft. Because of significant recent GEO spacecraft failures that have been shown in ground testing to be likely to also occur on LEO spacecraft, the SEE program commissioned the production of the new LEO Spacecraft Charging Design Guidelines (hereafter referred to as the LEO Guidelines). Now available in CD-ROM form, the LEO Guidelines highlight mitigation techniques to prevent spacecraft arcing on LEO solar arrays and other systems. We compare and contrast the mitigation techniques for LEO and GEO in this paper. We also discuss the extensive bibliography included in the LEO Guidelines, so results can be found in their primary sources.

Background

Historically, power systems on many space vehicles have operated at a nominal 28 V dc. At such low voltages, plasma interactions in LEO are negligible and have not been a consideration in spacecraft design. High power systems now being deployed for space applications operate at higher voltages in order to reduce power loss and system mass. The emergence of such systems is motivated primarily by a desire to save weight. Since the resistance of the necessary cabling is a decreasing function of mass per unit length and cable losses are proportional to current squared, it is desirable to furnish power at higher voltages and lower currents. A further consideration is the reduced effect of magnetic interactions (torque and drag) that will follow from low current operation.

While high voltage systems are clearly desirable to the power system designer, they suffer the drawback of interacting with the ionospheric plasma in several different ways. First, conducting surfaces whose electrical potential is highly negative with respect to the plasma can undergo arcing. Such arcing not only damages the material but results

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in current disruptions, significant EMI, and large discontinuous changes in the array potential.

One of the difficulties in predicting the onset of arcing has been the realization that the threshold potential for arcing depends critically not only on the design of the solar cells, but also in the manner cells are laid down and connected. In the early 1990's traditional wisdom focused on the observation that silicon cells using traditional silver coated interconnects exhibited a threshold potential for arcing of about -230 volts relative to the plasma (Ferguson, 1986). Yet, since that time, it has been shown that catastrophic failures can occur on operating solar arrays at much lower voltages. For example, the TEMPO-2 and PAS-6 solar array failures in 1997 (Snyder *et al*, 2000) were on solar arrays that operated at string voltages of 100 volts or less, and ground-tests showed that the Terra solar arrays (operating at 120 V) were liable to the same type of failure in LEO.

An additional effect that plagues surfaces at high negative potential lies in the fact that inbound ions, accelerated by the high fields, cause sputtering from surfaces with which they impact.

For solar arrays or other surfaces that are biased positively with respect to the plasma, a second effect occurs. Such surfaces collect electrons from the plasma, resulting in a parasitic loss to the power system. Since the mass of an electron is much less than an ion, the magnitude of current density is much greater for surfaces with positive bias. At bias potentials greater than about 150 volts, sheath formation and secondary electron emission from the surface causes the entire surrounding surface, normally an insulator, to behave as if it were a conductor. This effect, often referred to as "snapover" (Stevens, 1982), results in large current collection from even a very small exposed area.

Besides producing a power loss, currents collected by biased surfaces significantly affect the potentials at which different parts of the spacecraft "float." Because of their large mass and low mobility, ions collected by negatively biased surfaces result in a relatively small plasma current density. The lightweight electrons, on the other hand, are readily collected by positively biased surfaces. Ram and wake effects further complicate the picture. Ram energy is considerably higher than ambient thermal energy so ram flow enhances ion collection relative to surfaces that are oblique to the plasma flow.

A spacecraft, reacting to these various current sources, must necessarily reach equilibrium at whatever potential results in a net collected current of zero. The worst situations occur when the spacecraft power system uses a negative ground. In such a configuration, large surfaces are negative and must collect slow moving ions to balance the current from electron collection that now occurs only from relatively small areas of positive surface. In the worst case, parts of the spacecraft will be biased with respect to the ionosphere to a level very near the maximum voltage used on the solar arrays.

As experience has accumulated within industry and government, the need to capture the state of understanding has become pressing. Recognizing this, the Space

Environments and Effects (SEE) program, managed by the Marshall Spaceflight Center, has commissioned and funded a series of software design tools and guidelines documents to aid the spacecraft community. The latest of these efforts is the document reported here, which focuses on high voltage interactions in Low Earth Orbit (LEO), the LEO Spacecraft Charging Design Guidelines.

LEO vs. GEO

As most of the spacecraft design community is aware, charging conditions in Geosynchronous Earth Orbit (GEO) are severe, and are caused mainly by high energy electrons impinging on spacecraft surfaces during geomagnetic substorms (Rosen, 1975). In such events, spacecraft surfaces can charge differentially by as much as the energies of the incoming electrons, which may be as high as several kilovolts. Because spacecraft surfaces may have differing capacitances due to differing materials and grounding, and because differing materials may have differing secondary electron emission coefficients and other charging properties, a high degree of differential charging can occur that can lead to arcing conditions. On the other hand, the thermal plasma in GEO is so tenuous that the times required for the thermal plasma to discharge spacecraft surfaces can be many minutes. Under such conditions, the only way to prevent differential charging of spacecraft surface materials is to coat all exterior surfaces with conductive coatings, and connect them all to spacecraft ground. Then, although the spacecraft as a whole can charge several thousand volts negative, differential charging is eliminated, and the high electric field strengths necessary for surface plasma arcing are thereby eliminated.

The basic tenets for preventing arcing from GEO spacecraft charging were presented by Purvis, *et al* (1984). Over the years, these “Design Guidelines for Assessing and Controlling Spacecraft Charging Effects,” have become the spacecraft designers’ charging bible, sometimes to the extent that spacecraft designers have attempted to apply them in LEO conditions. This is a gross mistake. For example, some designers have attempted to make their solar array coverslides conductive enough to prevent differential charging in LEO by using poorly conductive coatings. These satisfy the GEO Guidelines but that fall many orders of magnitude below the conductivity that will bleed off the currents collected in the dense LEO plasma. In addition, these coatings can contribute to perpetually having snapover currents collected even on surfaces at low positive potentials. In other words, there is a big difference between charging in LEO and GEO and spacecraft designers should take this into account. Up until now, however, recommendations for designing for LEO charging have been scattered throughout the literature. This was one rationale for producing the LEO Spacecraft Charging Guidelines.

In the following, we will point out differences between recommendations for spacecraft charging in GEO, as taken from the Purvis *et al* (1984) technical paper and recommendations for spacecraft charging in LEO, as taken from the LEO Guidelines. For designing specific spacecraft, designers should read the LEO Guidelines in their entirety.

1. Surface materials and grounding

GEO – “For differential charging control, all spacecraft exterior surfaces shall be at least partially conductive. All conducting elements, surface and exterior, should be tied to a common electrical ground, either directly or through a charge bleedoff resistor.”

LEO – “Avoiding snapover has become a major design issue. Strategies include insulating all surfaces, where practical, and choosing insulators with low secondary electron emission yields. A thin insulator may undergo dielectric breakdown under the high electric field developed across it. Until the theoretical situation is better understood, plasma testing must be used to determine the dielectric strength of insulators.” If conducting surfaces are exposed, care must be taken to prevent them from arcing at conductor-insulator junctions.

2. Enclosures and shielding

GEO – “The primary spacecraft structure, electronic component enclosures, and electrical cable shields shall provide a physically and electrically continuous shielded surface around all electronics and wiring (Faraday cage).”

LEO – “If all high voltage components are inside a sealed pressure vessel, they cannot collect current from the ambient plasma (and LEO charging cannot occur). Encapsulation (or grouting with RTV) of solar arrays has been shown to be an effective method to prevent electron collection and charging (Reed *et al*, 2001). One must be careful with the use of encapsulants, however, when the possibility exists of outgassing in the presence of high voltage components. When encapsulating....no air must be entrained anywhere. The trapped air will present the danger of Paschen breakdown under high voltage. Also, to avoid plasma interactions, care must be taken that plasma does not enter the enclosure and react with exposed conductors inside. The key requirement on such systems is that all openings must be smaller than the plasma Debye length.”

3. Solar Arrays

GEO – “Solar panel back surfaces, edges, and honeycomb should be grounded conductors. The front surfaces of coverslides may be coated with a conductive, transparent coating of grounded tin oxide....” (Since 1997, when sustained arcing was discovered, some manufacturers have put restrictions on the spacing, string layout, and voltages of adjacent high voltage strings.)

LEO – “If possible, use array string voltages of less than 55 V. No trigger arcs have been seen on LEO arrays of less than about 55 V string voltage even under simulated micrometeoroid bombardment. Solar arrays coming out of eclipse will generate more voltage than when they operate at their max power point. If solar array cell edges or interconnects are exposed to the LEO plasma and string voltages are greater than 55 V, the strings should be laid out on the substrate such that no two adjacent cells have a voltage difference of greater than 40 V...” (to prevent sustained arcs).

4. Testing

GEO – Testing GEO spacecraft is mainly concerned with determining current paths when arcs occur, to prevent electronic upsets (ie “Internal (general) units must survive, without damage or disruption, the MIL-STD-1541 arc source test,” etc.). More recently, some testing has been done to determine the extent of charging, should it occur, and the likelihood of arcing due to the charging from a worst-case environment.

LEO – LEO testing is mainly concerned with trigger and sustained arc thresholds and arc-current waveforms. “If one is interested in investigating transient arcs, one must decouple the DC power supply from the arc current during an arc. This means the bias supply circuit must have a time constant greater than a few hundred microseconds, so the arc can build up and dissipate without being powered by the bias supply. This can be done by putting a large resistance in the arc circuit, and incorporating a capacitor to simulate the array or structure capacitance that would be discharged in the arc.”

5. Plasma contactors and other charge control devices

GEO – “Devices that emit neural plasmas or neutralized beams (e.g., hollow cathode plasma sources or ion engines) can maintain spacecraft potentials near plasma ground and suppress differential charging. These are therefore the recommended type of charge control devices.”

LEO – “Electron guns were used on PIX-II (Purvis, 1985) and PASP Plus (Guidice and Severance, 1998) to emit the electrons being collected by high voltage solar arrays and thus prevent charging, but such devices are limited by space charge considerations to low emitted electron currents. A better solution is a device that is not limited by space charge considerations, i.e. a plasma contactor.” “(The plasma contactor) current can be very large. For instance, the ISS PCU device has a hollow cathode element smaller than a little finger, but can emit up to 10 Amps of continuous electron current.”

In addition to the above topics and several others not listed here, the LEO Guidelines contains a special section on mitigation techniques for solar array arcing in LEO. Please see the LEO Guidelines for complete advice on all the topics listed above and more.

The LEO Guidelines Searchable Bibliography

An attempt was made to pull together all published sources of information about designing for the LEO plasma environment. In order to do this, the CASI database (Center for Aerospace Information) was searched for authors, keywords, and subjects related to LEO spacecraft charging. Over 300 abstracts were obtained, and are listed in chronological order in the LEO Guidelines Searchable Bibliography, located at the end of the same .pdf file as contains the LEO Guidelines. Because of the multiplicity of papers by the same authors in any one year, the CASI Document ID is used as a reference (i.e. Guidice *et al*, **19980017264** instead of 1998). While every attempt has been made for

completeness through the end of 2002, we are aware that we may have missed some references and are going to revise the Bibliography, if not the entire LEO Guidelines, every year to try to keep current and correct accidental omissions. To check the searchability of the Bibliography for this paper, we searched within Adobe Acrobat Reader for the name Guidice, and obtained fourteen references in the Bibliography within a few seconds.

Including the Bibliography, the LEO Guidelines comes to over 360 pages. It is recommended that the Guidelines be kept as a computer file reference book, or on CD-ROM, not as a printed reference. This will preserve the searchability feature, save trees, and make the LEO Guidelines completely portable, whereas a 360 page book is cumbersome, not searchable, and wasteful of natural resources. It is not believed that the LEO Guidelines contain any copyrighted, classified or ITAR restricted material, and may therefore be shared with anyone. The authors respectfully request that when material from it is used, we be given the proper credit (Ferguson, D.C. and Hillard, G.B., 2003, "Low Earth Orbit Spacecraft Charging Design Guidelines," NASA/TP-2003-21228, National Aeronautics and Space Administration Marshall Space Flight Center, MSFC, Alabama 35812, February 2003.) The LEO Guidelines has been proposed as a NASA standard. If that status is achieved, it may then be proposed as a world standard under ISO 9001.

Availability

The Low Earth Orbit Spacecraft Charging Design Guidelines is available from the NASA MSFC SEE website (<http://see.msfc.nasa.gov>) as part of the Charge Collector CD-ROM (version 2.0) or as a separate CD-ROM, or on CD-ROM directly from the authors at the address given for them in this paper. All authentic versions are in .pdf format. Neither the authors, the SEE program, or NASA are responsible for incorrect conclusions drawn from it by any party. It is intended solely as an aid for spacecraft designers to prevent harmful effects of LEO plasma interactions. The authors welcome comments and suggestions for improvements.

References

Ferguson, D.C., 1986, "The voltage threshold for arcing for solar cells in LEO: Flight and ground test results," NASA TM-87259, presented at the 24th AIAA Aerospace Sciences Mtg. and Exhibit, Reno, Nevada, Jan. 6-9, 1986.

Guidice, D.A. and Severance, P.S., 1998, "Chapter 3, Instrumentation," in **Photovoltaic Array Space Power Plus Diagnostics (PASP Plus) Experiment**, PL-TR-97-1013, by Guidice *et al*, the Air Force Research Laboratory, Kirtland AFB, March, 1997, p. 3-1 to 3-10.

Purvis, C.K., Garrett, H.B., Whittlesey, A.C., and Stevens, N.J., 1984, "Design Guidelines for Assessing and Controlling Spacecraft Charging Effects," NASA TP-2361, September, 1984.

Purvis, C.K., 1985, "The PIX-2 experiment: An overview", in **Spacecraft Environmental Interactions Technology-1983**, NASA CP-2359, AFGL-TR-85-0018, p. 321-332, NASA Lewis Research Center, March, 1985.

Reed, B.J., Harden, D.E., Ferguson, D.C., and Snyder, D.B., 2001. "Boeing's High Voltage Solar Tile Test Results, 17th Space Photovoltaic Research and Technology Conference, Ohio Aerospace Institute, September 11-13.

Rosen, A., 1975, "Large discharges and arcs on spacecraft," *Astronautics and Aeronautics*, vol. 13, June 1975, p. 36-44.

Snyder, D.B., Ferguson, D.C., Vayner, B.V., and Galofaro, J.T., 2000, "New Spacecraft-Charging Solar Array Failure Mechanism," 6th Spacecraft Charging Technology Conference, AFRL-VS-TR-20001578, pp. 297-301.

Stevens, N.J., 1982, "Review of biased solar array - Plasma interaction studies," AIAA PAPER 81-0738, AIAA, Japan Society for Aeronautical and Space Sciences, and DGLR, International Electric Propulsion Conference, 15th, Las Vegas, NV, Apr. 21-23, 1981, AIAA 16 p., International Electric Propulsion Conference Las Vegas, NV Apr. 21-23, 1981.

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